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Synchronous Reluctance Technology – Part I

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I. INTRODUCTION

In recent years, the desire for high efficiency and high torque density electric motors has significantly increased. In the industrial arena, the EU Commission Regulation (EC) No 640/2009 implementing Directive 2005/32/EC has prompted the IEC to issue new energy efficiency standards (under IEC 60034-30) for electric motors, aimed at reducing energy consumption to help tackle greenhouse gas emissions (GHG) and climate change. Approximately 60% of all generated electricity in the EU and is fed into electric motors, whether this be to factories such as paper mills or plastic goods manufacturing, for common industrial fan and pump applications or consumer goods. Over 90% of these motors are of the induction type (IM), mostly three phase four pole, powered either direct on-line (DOL) or via a variable speed drive (VSD). These consume approximately 64,000 GWh of energy per annum [1], corresponding to approx. 35 Mt of GHG emissions [2]. The proposed IE4 super-premium efficiency standard, aims to increase machine minimum efficiency to help tackle the issue. We are already seeing the marketing of IE4 efficiency standard machines, both induction and synchronous reluctance, such as those in Fig. 1 by ABB.



Fig. 1 ABB Synchronous Reluctance Motor and Drive Package, Courtesy:<http://www.abb-conversations.com/2012/11/ie4-synchronous-reluctance-motor-drive-package-on-sale-this-week/>.

The second stream for high efficiency and torque density motors is the traction motor market. In 2011, there was a price bubble affecting the £/kg of Rare Earth Elements, to such an extent that it kick-started a push for alternative technology. In fact, the price of rare earth oxides rose from 75 \$/kg to 325 \$/kg in a ten month time frame, a rise of over 300%. This, accompanied by the political and supply chain issues that caused the price bubble, the environmental

concerns with extracting and processing the material and the scarceness of economical mining activity has boosted the drive for rare-earth free technologies. As of early 2014 the vast majority of marketed electric vehicles contain PM machines with PM weights of between 1-2kg, and at a projected 80,000/year electric vehicle market by 2020 [3], this equates to a large volume and a large cost of just PM material. This is highly undesirable and new technology must be embraced.

This two part series presents an alternative technology that is a current research topic in industry and academia, focussed on addressing the above issues. This first part outlines the advantages and disadvantages of SynRM technology and briefly compares it to common IM and PMSM technologies. The second part digs deeper into current research topics and bring the reader upto speed with recent developments and applications while exploring the road ahead for this technology.

II. BRIEF HISTORY

Synchronous reluctance technology (SynRM) as it is known today was first published by Kostko in 1924 [4], his ‘polyphase reaction motor’ was a different type of reluctance motor than the age old switched reluctance motor (SRM) which was first introduced about 100 years before. The switched motor was first introduced on the Caledonian Railway in Scotland as a locomotive traction motor (which could not propel the locomotive faster than a few men pushing!) [5]. The first SynRMs had relatively low performance, utilizing simple salient rotors or modified induction machine rotors, which sometimes still incorporated a cage for starting. Because of the poor synchronous performance, this motor type was left mainly neglected until the 1960/70’s, where the work of [6] Lawrenson [6], Cruickshank [7] and Honsinger [8] among others aided the advancement of the SynRM. Engineers requiring synchronised machines in applications such as in paper mills, investigated the SynRM and a number of new designs were developed, however with no variable frequency drives (in their current form) available at that time, application (and interest in) once again faded. In the 1980/1990’s, power electronics had developed rapidly after the computer revolution in the 1970’s, engineers in the 1980/90’s such as Miller [9] and Staton [10] then revisited this technology. Variable frequency drives were now becoming readily available and again, a renewed interest in SynRM came about, however, in this same period, the advent of Rare Earth Permanent Magnets once again foiled further development. The rare earth permanent magnet motors (PMSM) had inherent advantages over the existing SynRM technology at that time and thus it appears that the SynRM has been consistently upstaged by more fashionable or convenient technologies. Extensive research and development in rare earth PMSM machines has existed since their inception, but in 2011, as mentioned, the rare earth crisis hit, coupled with the

new IE4 efficiency standard the synchronous reluctance motor has once again been resurrected.

III. TYPICAL CONSTRUCTION

The synchronous reluctance motor is a true AC rotating field machine, requiring a balanced polyphase sinusoidal supply into a distributed winding, which for all intents and purposes is identical to that of the induction machine of the same power rating. The rotor component is typical of general reluctance technology, usually consisting of only iron (when controlled by a VSD) but has been known to also incorporate a cage (for DOL applications). The more common switched reluctance motor requires a non-standard converter. There are two rotor variants, the transverse laminated type and the axially laminated type, which are examined in Section VI.

IV. OPERATING PRINCIPLE

As the SynRM is a rotating field AC machine that develops only a reluctance torque, the key to operation is anisotropic magnetic reluctance in the rotor. In any reluctance based machine, in a decoupled reference frame if the d (*direct*) -axis is termed the path of least reluctance and the q (*quadrature*) -axis is the path of greatest reluctance (inverse saliency when compared to the PMSM). In an energised system such as in Fig. 2, the rotor will tend to align with the energised coil (to maximise inductance or minimise magnetic reluctance/energy) via a reluctance torque produced by the Lorentz force. If the aligning field is constantly rotating around the airgap periphery of a polyphase distributed winding stator and the current phase controlled such that the rotor is always trying to maximise the inductance, a constant torque (ideally) will be produced. This results in a synchronous machine that develops only a reluctance torque.

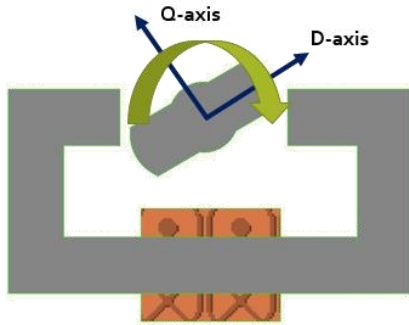


Fig. 2 A Simple Reluctance Motor

V. FIGURES OF MERIT

It is common that d - q axis theory is the analysis of choice for AC machinery with polyphase sinusoidally distributed stator windings. The torque expression for the machine as;

$$t = p(L_d - L_q)i_d i_a = \frac{p}{2}(L_d - L_q)i_s^2 \sin(2\kappa)$$

Where κ is the machine current angle, i.e. the angle between the current vector and the d -axis of the machine. It is easy to see that the current angle must be at 45 degrees (half way between the d and q axes in electrical terms) for maximum torque. The equation is similar to that of an interior permanent magnet d - q model, with the permanent magnet term removed. This d - q theory leads us to two figures of merit;

- **Saliency Ratio** – *physically relating to the level of anisotropic magnetic reluctance of the rotor and the machine power factor.*

$$\xi = \frac{L_d}{L_q}$$

- **Torque Index** – *indicates the torque capability of the machine.*

$$\theta = (L_d - L_q)$$

These figures of merit indicate the performance of the machine. A rotor design must maximise the d -axis inductance and minimise the q -axis inductance for maximum power factor and torque production. The higher the saliency ratio, the more the general performance of the machine increases. Typical saliency ratios in high performance modern designs are between 6 and 8.

Figure 3 indicates the maximum achievable power factor for two control modes, maximum power factor control (MPFC) and maximum torque per ampere (MTPA), these are selected by adjusting the machine current angle to 75deg and 45deg respectively. It is evident that the power factor, for practical saliency ratios, in maximum torque per Ampere mode is severely limited.

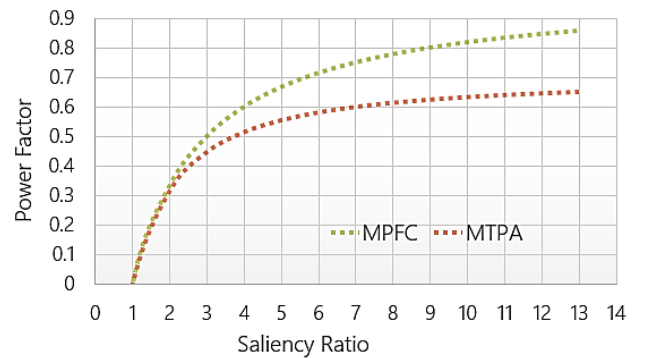


Fig. 3 Power Factor curves with saliency ratio

VI. ROTOR CONSTRUCTIONS

A number of different rotors have been explored for the synchronous reluctance machine. These range from simple salient type to axially laminated types. Figures 4 to 7 illustrate the different topologies.

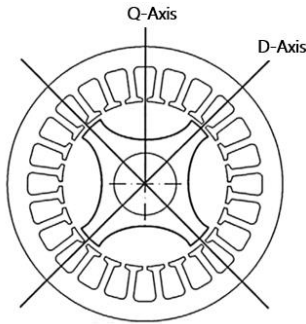


Fig. 4 Salient pole rotor, courtesy of [11]

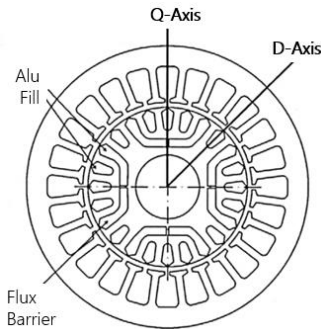


Fig. 5 Flux barrier with cage rotor, courtesy of [11]

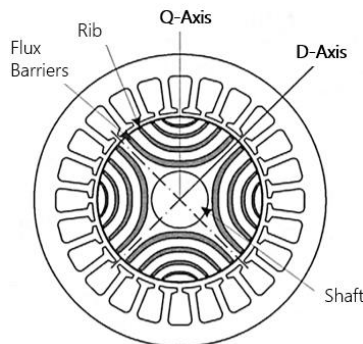


Fig. 6 Cageless Flux barrier rotor, courtesy of [11]

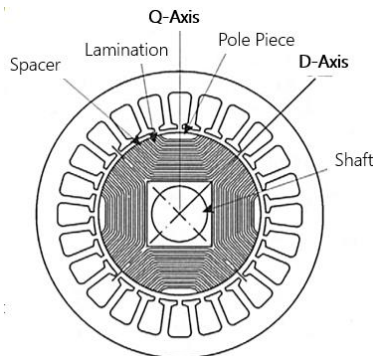


Fig. 7 Axially laminated rotor, courtesy of [11]

The simple salient rotor (Fig. 4) is very easy to construct, but it has a very poor saliency ratio, usually ≤ 2 , and is therefore generally not considered. However, due to its shape it can potentially run at very high speeds. The caged-flux barrier rotor (Fig. 5), is

essentially a synchronous induction motor, with the cage only used for starting (or possibly damping oscillations of the rotor). The cage requirement limits the electromagnetic design of the rotor and thus the maximum saliency ratio that can typically be achieved is ≤ 4 . There is a casting and punching process, identical to that of the induction machine, but it does have the benefit of synchronism when up to rated speed. The next topology, is the cageless flux barrier design (Fig. 6), and is usually the topology of choice due to its high saliency ratios by good electromagnetic design. Typical saliency ratios for this topology are in the region $6 \leq \xi \leq 10$. They have no casting process but do require a variable frequency drive for operation. The flux barriers guide the flux and thus act to minimise the q-axis inductance and simultaneously maximise the d-axis inductance. The final design, is axially laminated (Fig. 7), i.e. the laminations are oriented with the shaft centre axis. This type of design has high saliency ratios ($8 \leq \xi \leq 13$), which offers the best electromagnetic performance, but are difficult to construct with problems of large eddy current losses due to lamination direction.

VII. COMPARISON WITH TRADITIONAL INDUCTION MACHINES

The SynRM can be derived from induction machines, simply by removing rotor bars and introducing saliency to the rotor. Around 80% of the torque can be retained for 60% of the loss [12], hence the SynRM is a competitive technology. Inherent advantages of SynRM technology over IM technology include;

- Rotor synchronicity
- No rotor conductors
 - Increased robustness
 - Lower maintenance / cost
- No rotor copper loss
 - Thermal improvements
- Higher efficiency
- Higher torque density
- Lower rotor inertia
 - Faster torque dynamics
- Easier to implement control schemes

Characteristics that could be considered disadvantages are;

- No-direct online capability (without caged rotor)
- Lower power factor
 - Potentially increased inverter requirement
- Immature technology
- Not widely manufactured or available (yet)

With regard to design, in one case, the SynRM can be designed for the same frame size as an equivalent power IM, but achieve the latest IE4 efficiency standard rating.

In contrast, the machine frame size can be reduced and for the same loss condition the same or increased output can be achieved. The majority of the losses in the synchronous reluctance machine are confined to the stator copper windings, where it is generally easier to remove heat than the rotor, which is a major challenge in the IM.

VIII. COMPARISON WITH PERMANENT MAGNET MACHINES

Like the SynRM, the PM synchronous machine is synchronous with the stator field and contains no rotor conductors. Hence the rotor loss is less than the IM (at low speed), however, the machine does typically contain expensive permanent magnets, which are lossy in their own way. There is no doubt that the permanent magnet machine exhibits higher torque density and superior inverter utilization.

The apparent advantages of SynRM technology over PM technology include;

- No permanent magnets
 - Significantly lower cost
 - Easier assembly and manufacture
 - No PM demagnetisation risk
 - No material supply issues
 - No PM short circuit current
 - No magnet loss
- Increased robustness

Again, characteristics that could be considered disadvantages against PM technology are;

- Lower torque/volume and torque/mass
- Lower power factor
 - Increased inverter requirement
- Lower torque per unit loss (at low speed)
- Not widely manufactured or available (yet)

There are a number of benefits of removing PM material from AC machines, and much effort is now underway to develop the SynRM, so that they can better compete with the performance of PM based machines. However, there are a number of challenges ahead, which will be detailed and solutions presented in Part II of this series.

IX. SUMMARY

With the engineering challenges that lay ahead, higher efficiency and higher torque dense PM-free motors are enjoying a renewed research interest. The SynRM has a rocky history in its development but it is now being reconsidered for future applications. It operates developing only a reluctance torque and is a true AC rotating machine that contains no rotor conductors or magnets. It enjoys inherent benefits, over that of

induction machine and permanent magnet technologies, however PM machines enjoyed continuous research with many millions of GBP spent on their development. This is in contrast to the SynRM which has had a fraction of that attention and expenditure. With this in mind, it is hoped that developments in SynRM technology can provide engineering solutions for many applications.

X. REFERENCES

- [1] DUKES 2013 Chapter 5: Electricity, Department of Energy & Climate Change, 2013
- [2] <https://www.gov.uk/government/publications/provisional-uk-emissions-estimates>; Department of Energy & Climate Change, 2013
- [3] 'VW joins rush into electric vehicles', Financial Times, March 8, 2010, <http://www.ft.com/cms/s/0/224a0132-2ad7-11df-886b-00144feabdc0.html>
- [4] Kostko, "Polyphase Reaction Synchronous Motor", Journal of AIEE, vol 42, 1923, pp. 1162-1168
- [5] J. Reid, 'Robert Davidson – Pioneer Electrician', The Scientific Tourist: Aberdeen, Aberdeen University
- [6] Lawrenson, P.J.; Agu, L.A., "Theory and performance of polyphase reluctance machines," Electrical Engineers, Proceedings of the Institution of , vol.111, no.8, pp.1435,1445, August 1964
- [7] Cruickshank A.J.O. et al: "Theory and performance of reluctance motors with axially laminated anisotropic rotors", Proc. IEE, vol 118, no. 7., 1971
- [8] Honsinger V.B.: "The inductances Ld and Lq of reluctance machines", IEEE Trans. PAS, vol 90, no. 1., 1971
- [9] Miller, T. J E; Cossar, C.; Hutton, A.J., "Design of a synchronous reluctance motor drive," Industry Applications Society Annual Meeting, 1989., Conference Record of the 1989 IEEE , vol., no., pp.122,127 vol.1, 1-5 Oct. 1989
- [10] Staton, D.A.; Soong, W.L.; Miller, T. J E, "Unified theory of torque production in switched reluctance and synchronous reluctance motors," Industry Applications, IEEE Transactions on , vol.31, no.2, pp.329,337, Mar/Apr 1995
- [11] Betz Robert Eric, 'Modeling and Control of Synchronous Reluctance Machines', Control in Power Electronics Selected Problems, Academic Press, USA, 251-299 (2002) [B1]
- [12] Lipo T.A.: " Synchronous reluctance machines – a viable alternative for AC drives ," Electr Mach Power Syst, vol. 19, pp. 659-671, 1991